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ELECTROMAGNETIC EFFECTS IN THE NEIGHBORHOOD OF AN ARTIFICIAL SATELLITE OR A SPACECRAFT MOVING THROUGH THE IONOSPHERE OR INTERPLANETARY SPACE *[/3]

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The author discusses the effects arising in the neighborhood of a body moving through the ionosphere or the interplanetary medium, and the nature of their variation with growing distance between the body and Earth. The results of theoretical calculations of different disturbances are examined: variation in the concentration and flux of particles; potential of the body; scattering; electrical field; excitation of longitudinal plasma waves; evaporation. Certain published experimental findings on these effects are utilized.

Author

INTRODUCTION

The orbit of an artificial satellite or spacecraft passes through strongly rarefied plasma and also through fields of different types of radiation. The interaction between these bodies and the surrounding particles and the effect of particle fluxes on them lead to the appearance of different effects around the body. The relaxation times of these effects are relatively small. Therefore, most of the effects set in when the body travels over distances that are much shorter than the distances over which the properties of plasma or of a radiation field change. Thus, a complex of effects travels along with the satellite or spaceship moving through the plasma. The nature of these effects

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* Numbers in the margin indicate pagination in the original foreign text.

changes with time and depends both on the properties of the body - its dimensions, shape, velocity, the photochemical features of the matter of which it consists - and on the properties of the plasma and the radiation field. By means of various types of measurements, the nature of the variations in the effects arising around the body can be recorded or, conversely, if the patterns of these variations are known, the properties of the medium can be investigated by referring to the nature of these effects. It is obvious that, to investigate the properties of the unperturbed medium through which a satellite or spaceship moves, the influence of these effects on the results of different measurement techniques must also be known.

The complex whole of the effects arising around a body and the properties of the media through which that body moves are extremely varied. What is more, the properties of the same body vary greatly with respect to the characteristic constants of plasma when passing through different media. The state of the theoretical interpretation and experimental investigation of the different effects also varies extensively. Therefore, a unified treatment of the problem with its many broad and varied aspects is extremely difficult at present.

Below, an attempt is made to examine the overall state of this problem in a manner that is to some extent fragmentary. To this end it is primarily necessary to describe the principal properties of the media through which the artificial satellites and spaceships move, as well as certain properties of these bodies themselves.

Section 1. Characteristic Properties of Media

The orbits of artificial satellites and outer-space rockets intersect a /4 plasma whose physical parameters vary widely. It is expedient to subdivide it into regions according to the variation in the nature of the effects in the neighborhood of the moving body. The principal physical parameters of these media are given in Table 1.

TABLE 1

PRINCIPAL PARAMETERS OF PLASMA

Physical Parameter	Range of Distances from Earth				
	250—400. km Medium I	600—700, km Medium II	3000. km Medium III	(5—10) R_e Medium IV	Interplanetary Medium (50—100) R_e Medium V
Neutral particle concentration n_o, cm^{-3}	$10^{10} - 10^{9}$	10^7	$10^4 - 10^3$	—	—
Electron and [redacted] N_o, cm^{-3}	[illegible]$(10^5 - 10^6)$	10^5	(?) $10^3 - 10^4$	$10^{[illegible]}$	10 — 1
Temperatu[redacted]	~ 1000	~ 2000	~ 4000	~ 5000	?
Molecular weight of particles M_o	24	16	1	1	1
Number of collisions between neutral particles $\nu_{nn} \sim \nu_{ni}$, sec^{-1}	~ 1	—	—	—	—
Effective number of electron collisions $\nu_{e(n+1)}$	$(1-3)\cdot 10^3$	$(1-3)\cdot 10^2$	~ 10	10^{-2}	—
Mean free path of neutral particles ℓ_n, cm	$(1-7)\cdot 10^5$	$(1-5)\cdot 10^7$	$2\cdot 10^{14}$	—	—
Mean free path of electrons and ions $\ell_{e,i}$, cm	10^4	10^5	10^6	10^9	—
Mean thermal velocity of neutral particles and ions $v_{n,i}$, cm/sec	~ 10^5	$1.5\cdot 10^5$	$(6\div 10)\cdot 10^5$	$2\cdot 10^6$	—
Mean thermal velocity of electrons v_e, cm/sec	$2\cdot 10^7$	$3\cdot 10^7$	$4\cdot 10^7$	$5\cdot 10^7$	—
Plasma frequency of electrons ω_o, sec^{-1}	$(1-5)\cdot 10^7$	10^7	$5\cdot 10^6$	10^6	10^5
Plasma frequency of ions Ω_o, sec^{-1}	$(0.5-2.5)\cdot 10^4$	$6\cdot 10^4$	$6\cdot 10^4$	$2\cdot 10^4$	$2\cdot 10^3$
Magnetic field H_o, oe	0.45	0.35	0.16	$2\cdot 10^{-3}$	10^{-5}
Larmor frequency of electrons ω_H, sec^{-1}	$7.5\cdot 10^6$	$6.5\cdot 10^6$	$3\cdot 10^6$	10^5	10^4
Larmor frequency of ions Ω_H, sec^{-1}	$2\cdot 10^2$	$2\cdot 10^2$	$8\cdot 10^2$	10^2	10
Larmor radius of electrons ρ_{H_e}, cm	3	4	10	10^2	10^3
Larmor radius of ions ρ_{H_i}, cm	$5\cdot 10^2$	$8\cdot 10^2$	10^3	10^4	10^5
Debye radius D, cm	0.5	0.5	3	$3\cdot 10$	$5\cdot 10$

First of all, we will isolate the region of 250-400 km altitudes, adjoining the principal maximum of the ionosphere - medium I. Here, the electron concentration varies slowly with altitude and reaches, under different conditions, its maximum $N_m = (1 - 5) \cdot 10^6$ el/cm^3 (Bibl.1).

The principal distinguishing features of media II and III are as follows. In this region of the outer ionosphere, most plasma parameters vary monotonously. According to recent findings, however, the composition changes rapidly at altitudes of 800 - 1400 km. Thus, atomic oxygen predominates at altitudes /5 of 700 - 1000 km; helium, at 1000 - 1200 km; and hydrogen, above 1400 km. As a result, on passage from medium II to medium III, the ion velocity increases rapidly, which is extremely important for examination of the effects with which we are concerned.

The region of plasma near the Earth, at distances of 5 - 10 earth radii (R_0) from Earth's center (medium IV) has a number of features by which we may classify it as the boundary portion of the gas envelope of the Earth. This manifests itself chiefly in that the effect of the Earth's magnetic field in this region is still appreciable. This, in particular, leads to the formation of radiation belts; the effects with which we are concerned are greatly affected by the fact that here the pressure of the magnetic field $H_0^2/8\pi$ still exceeds the pressure of the gas $N_0 \varkappa T$.

There exist few reliable data on medium V. Note that the values of the magnetic field measured at those distances show that apparently there $H_0^2/8\pi \lesssim N_0 \varkappa T$, i.e., the effect of the outer magnetic field on particle motion decreases markedly. No reliable data on the particle temperature in this plasma region are available, but the fact that the thermal velocity of ions v_i in medium V is several times as high as 10^6 cm/sec can be used as basis.

A common feature of plasma is the considerable length of the mean free path $\ell_{n,i,e}$ of all the particles and the rapid increase in ℓ with increasing distance from the Earth's surface; throughout, ℓ greatly exceeds the size of the moving bodies (Table 1). Therefore, the theoretical solution of different problems requires a kinetic approach based on Boltzmann equations. Although the neutral particle concentration at lower altitudes is high and considerably exceeds the electron and ion concentrations, collisions between neutral particles and ions are extremely rare. Therefore, the influence of the motion of neutral particles on the investigated electromagnetic effects and collective phenomena (electromagnetic waves and vibrations arising in the presence of a charged gas) may be disregarded. The medium can be considered throughout as a completely ionized plasma. In this connection, up to altitudes of approximately 1000 - 3000 km, when analyzing certain effects, collisions between charged particles must be taken into account. Media IV and V, however, may already be considered collision-free.

A thorough investigation of the effects in question here requires the joint solution of kinetic equations and Poisson's equation. Here, the magnetic field markedly affects the motion of charged particles, so that the Earth's magnetic field must be taken into account if a correct picture of a number of effects is to be obtained.

It is worth noting that, apparently, the medium is quasineutral throughout, i.e., the undisturbed concentrations of electrons and ions are equal, $N_{0_e} \sim N_{0_i}$. We also proceed from the premise that the unperturbed medium is in quasithermal equilibrium, i.e., the electron and ion temperatures differ little. This is highly significant with respect to the effects considered, since the Landau damping decreases if $T_e \gg T_i$, which contributes to the plasma instability.

In theory, the problem of investigating electromagnetic effects in the neighborhood of bodies moving in a plasma, in a coordinate system moving together with the body, reduces to the solution of the system of equations:

$$
\begin{gathered}
\frac{\partial f_i}{\partial t}+\bar{v}\frac{\partial f_i}{\partial \bar{r}}+\frac{e\bar{E}}{M_i}\frac{\partial f_i}{\partial \bar{v}}+\frac{e}{M_i c}[\bar{v}+\bar{V}_0, \bar{H}_0]\frac{\partial f_i}{\partial \bar{v}}=Y_i,\\
\frac{\partial f_e}{\partial t}+\bar{v}\frac{\partial f_e}{\partial \bar{r}}-\frac{e\bar{E}}{m}\frac{\partial f_e}{\partial \bar{v}}-\frac{e}{mc}[\bar{v}+\bar{V}_0, \bar{H}_0]\frac{\partial f_e}{\partial \bar{v}}=Y_e,\\
\Delta\varphi=-4\pi e\left\{\int (f_i-f_e)\,d^3v\right\}, \quad E=-\operatorname{grad}\varphi,
\end{gathered}
\tag{1}
$$

/6

where $f_i(t, \bar{r}, \bar{v})$ and $f_e(t, \bar{r}, \bar{v})$ are the required particle distribution functions (Bibl.2, 3). At sufficiently great distances from the body, where the plasma is not perturbed, the distribution functions are maxwellian

$$
\begin{gathered}
f_{i0}=N_0\left(\frac{M_i}{2\pi\varkappa T}\right)^{3/2}\exp\left\{-\frac{M_i(\bar{v}+\bar{V}_0)^2}{2\varkappa T}\right\},\\
f_{e0}=N_0\left(\frac{m}{2\pi\varkappa T}\right)^{3/2}\exp\left\{-\frac{m(\bar{v}+\bar{V}_0)^2}{2\varkappa T}\right\}.
\end{gathered}
\tag{2}
$$

Since the electron velocity $v_e = \sqrt{2\varkappa T/m}$ considerably exceeds the velocity of the moving body V_0, the electron distribution around the body may [apart from isolated cases ($\bar{V} \parallel \bar{H}_0$)], be described in the quasistationary case by the Maxwell-Boltzmann function

$$
f_e=N_0\left(\frac{m}{2\pi\varkappa T}\right)^{3/2}\exp\left\{\frac{e\varphi(\bar{r})}{\varkappa T}-\frac{m(\bar{v}+\bar{V}_0)^2}{2\varkappa T}\right\}.
\tag{2a}
$$

If we consider only the stationary state of these effects, i.e., if we disregard the question of establishment of the field and concentration of the particles or the question of their stability, as well as the question of the emission of electromagnetic waves by the body, then the functions f_e and f_i are not time-dependent and in eqs.(1) we will have $\partial f_e/\partial t = 0$, $\partial f_i/\partial t = 0$. In investigating the stability or emission, it is expedient to perform the examination in a coordinate system that is fixed with respect to the body.

The right-hand part of eq.(1) contains collision integrals, i.e., functions that take account of the influence of particle collisions on the distribution functions. In a number of cases, e.g. when calculating particle concentrations over distances commensurate with the size of the body, particle collisions may be disregarded, i.e., we may assume $Y_i = 0$, $Y_e = 0$. With respect to certain effects, however, such as scattering of radio waves in the wake of the body, in which the entire region of perturbation participates, the consideration of collisions is fundamental, since it restricts the divergence of the corresponding variables.

To the right-hand parts of the kinetic equations (1) we must also add functions that take the boundary conditions at the body surface into account. These functions should include a large set of effects and describe the nature of the reflection or scattering of particles by the surface - the relationship between the corresponding distribution functions. Allowance must be made for the measure of the absorption or neutralization of charges, the particle accommodation, and the "production" of particles due to evaporation or disintegration of the body, owing to the photoeffect, under the action of incident fluxes, etc. Many of these effects are still relatively uninvestigated. In the examination of some of these effects, the role of boundary conditions may be decisive, for example, in the problem of the stability or emission of the body. On the other hand, the effect of boundary conditions on radio-wave scatter against the wake of the body is relatively inessential.

Section 2. Characteristic Properties of Bodies

Consider the nature of the relative variation in the dimensions and velocity of a body (either satellite or space rocket) receding from the Earth (see

Table 2). Let the linear dimension of the body be $\rho_0 \sim 10^2$ cm. It should be borne in mind, however, that the dimensions of the instruments used (e.g. various kinds of probes) are of the order of 1 - 10 cm, which is one or two orders smaller than the dimensions of the body. With respect to certain effects it is exactly the linear dimension of the instrument, rather than that of the body itself, which may play the decisive role. /7

TABLE 2

PRINCIPAL PROPERTIES OF BODIES

Parameters of Moving Body	Range of Distances from the Earth, km				
	250—400 Medium I	600—700 Medium II	3000 Medium III	$(5-10)R_e$ Medium IV	Interplanetary Medium $(50-100)R_e$ Medium V
Linear dimension of body, ρ_o, cm	10^2	10^2	10^2	[illegible]	10^2
Velocity of body V_o, cm/sec	$(8-11)\cdot 10^5$	$(8-11)\cdot 10^5$	$(8-11)\cdot 10^5$	$(5-4)\cdot 10^5$	$2\cdot 10^5$
Ratio of velocity to linear dimension $F_o = V_o/\rho_o$	$\sim 10^4$	$\sim 10^4$	$\sim 10^4$	$\sim 5\cdot 10^3$	$\sim 2\cdot 10^3$
Ratio of V_o to thermal velocity of ions V_o/v_i	$8-11$	$5-7$	$\simeq 1$	0.2	$\ll 1$
Ratio of ρ_o to Debye radius ρ_o/D	$2\cdot 10^2$	$2\cdot 10^2$	30	3	2
Ratio of $2\pi F_o$ to plasma frequency of ions $2\pi F_o/\Omega_o$	$10-2$	1	1	3	30
Ratio of $2\pi F_o$ to plasma frequency of electrons $2\pi F_o/\omega_o$	$10^{-3}-10^{-2}$	10^{-2}	10^{-2}	$3\cdot 10^{-2}$	10^{-1}
Ratio of $2\pi F_o$ to Larmor frequency of ions $2\pi F_o/\Omega_{Hi}$	$3\cdot 10^2$	$\sim 3\cdot 10^2$	$\sim 10^2$	$\sim 5\cdot 10^2$	$\sim 10^3$
Ratio of ρ_o to Larmor radius of ions ρ_o/ρ_{H_i}	~ 0.2	~ 0.1	~ 0.1	$\sim 10^2$	$\sim 10^{-3}$
Ratio of ρ to Larmor radius of electrons ρ_o/ρ_{H_e}	~ 30	~ 25	~ 10	1	0.1

As it recedes from the Earth the space rocket or satellite with a prolate orbit loses velocity, reaching approximately 2×10^5 cm/sec in the interplanetary medium (at 100 R_0). This is accompanied by a rapid increase in the thermal velocity of the ions owing to the decrease in the molecular weight of the particles and the increase in temperature. Thus, while we have $V_0/v_i \gg 1$ near the Earth, i.e., at altitudes $\lesssim 1000 - 2000$ km, it appears that $V_0/v_i \sim 1$ at an altitude of ~ 3000 km and $V_0/v_i \ll 1$ above that altitude.

Accordingly, in the media II - III the body moves at supersonic velocity with a high Mach number V_0/v_i. This determines the nature of the effects in its neighborhood. Since, however, the media considered are not a "gas continuum", the effects arising here are not of a hydrodynamic nature. For example, no shock waves form ahead of the body. The perturbed region is aft of the body and somewhat resembles a Mach cone; but this resemblance is purely formal, the perturbance being of a different nature and its structure being markedly dependent on the electric field. Therefore, to avoid confusion, it is not advisable here to employ hydrodynamic terminology such as Mach number, Mach cone, etc.

On transition from the medium II to the medium IV, the body passes through a region where its velocity is commensurate with the ion velocity. The theory of this case is the most difficult to investigate, and the experimental data available for these plasma regions also are scarce. Lastly, in the media IV /8
and V the nature of the effects in the vicinity of the moving body is close to the effects around a quiescent body, since there $V_0/v_i \ll 1$.

The magnetic field exerts throughout a great influence on the motion of particles in the neighborhood of the body. This influence, however, apparently diminishes on transition to the medium V.

As the body recedes from the Earth, its size at first greatly exceeds the Debye radius, i.e. $\rho_0 \gg D$, but subsequently ρ begins to approximate D. This means that in the first case (media I, II) owing to Debye shielding, the collective effects of the motion of charged particles are actually significant at any distance from the body. In regions III and IV where $(r - \rho_0) < D$ the field decreases in accordance with the Coulomb law. Thus, the media I, II, III differ markedly with respect to, for example, the distribution of particle concentration, the particle-flux incidence on the body as a function of the potential of the body, etc.

Table 2 also distinguishes a third parameter - the ratio of the velocity of the body to its size, $V_0/\rho_0 = F_0$, which may be a criterion of the frequency of "natural" oscillations of the body and conditionally serve as a yardstick of the anticipated spectrum of oscillation frequencies and waves excited or emitted in the plasma by the moving body. So far, these questions have been relatively uninvestigated. Therefore, the analysis of the anticipated effects is based exclusively on variational equations. It is not impossible, however, that the frequency F_0 and the degree of its closeness to other characteristic plasma frequencies plays a role in the processes of excitation or stability of the plasma in the vicinity of the body. Table 2 indicates that the "natural" frequency of the body is commensurate with the plasma frequency of ions in virtually all of the media considered.

The ratio of the dimensions of the body to the Larmor radius may, along with the pressure $H_0^2/8\pi$, serve as another criterion of the influence of the outer magnetic field on the effects in the neighborhood of the body. Table 2 shows that, as far as a distance of several earth radii, the Larmor radius of electrons is smaller than the radius of the moving body. Under these conditions, it is essential to take into account the influence of the magnetic field, e.g. when calculating the electron flux throughout the neighborhood of the body. As for the Larmor radius of ions, it is everywhere greater than the size of the body and thus the influence of the ion precession on ion flux is less marked close to the body. On the other hand, ion precession around the magnetic field leads to a quasiperiodic extended structure of the perturbation in ion concentration around the body, which considerably intensifies the radiowave-scatter effects in the wake of the body.

We have already pointed out the important role that may be played by the effects occurring at the boundary of the body and depending on its velocity, its surface structure, its constituent matter, the properties of the plasma, as well as on the field of emission and fluxes in which the body is moving. The influence of the boundary manifests itself in a twofold manner, despite the large number of phenomena occurring in its vicinity.

First, the distribution function of the particles incident on the body varies in accordance with their reflection, which affects the nature of particle distribution in the vicinity of the body. Here, particle reflections of different types are possible: specular, i.e., without loss of velocity; elastic-diffuse, i.e., without loss of velocity but with an equiprobable variation in the direction of velocity after scattering; inelastic (accommodation), where velocity is lost and the direction can be arbitrary; partial or total neutralization of charged particles at the surface, etc.

Second, another group of effects (evaporation from the surface, erosion due to collisions with particle fluxes or with meteoritic matter, electron or ion photoemission, etc.) leads to the "production" of new particles around the body.

It is convenient to describe both groups of effects by means of terms of 19
a common kind, added correspondingly to the right-hand parts of the kinetic equations (1)

$$A_{e,i}(\bar{r}_s, \bar{v}_1, \bar{v})\delta(S), \tag{3}$$

where $\bar{r}_s$ defines a point on the body surface; $\bar{v}_1$ and $\bar{v}$ are the particle velocities before and after collision with the body, respectively. Depending on the physical statement of the problem, the functions A_e and A_i then assume one form or another and may, in particular, include several terms each of which describes processes of a different nature. Clearly, the δ-function $\delta(S)$ entering in eq.(3) characterizes the fact that the functions A_e and A_i are non-zero only at the surface of the body.

The physical meaning of the functions A_e and A_i is understandable: by definition, $A\delta(S)$ with respect to dimension is df/dt; therefore,

$$\int A d^3v = J$$

represents the variation in the number of particles (J cm^{-2} sec^{-1}) per second over a unit surface area, due to the influence of the body: owing to collision with its surface or owing to the production of new particles.

Section 3. Disturbance in Particle Concentration

A. Rapidly moving body, $V_0/v_i \gg 1$. In the plasma regions where $V_0/v_i \gg 1$, i.e., up to altitudes of ~2000 km, the concentration in front of the body increases - a condensation region forms in front of the body (Bibl.2, 4, 5). The concentration $N(r, \theta)$ is maximal near the very surface of the body and rapidly decreases obeying the law of $\delta N = (N - N_0) \sim N_0(\rho_0/r)^2$. At a distance of several radii ρ from the body, $N(r, \theta)$ no longer differs much from the undisturbed particle concentration N_0. Naturally, $N(\bar{r})$ in the condensation region depends considerably on the scattering properties of the body surface.

The most typical and important feature of the disturbances $N(\bar{r})$ is the formation of an extended wake aft of the body in the form of a zone of rarefaction. The decrease in $N(\bar{r})$ aft of the body is attributable to the ejection of ions by the body and the formation of a rarefied electrically charged inhomogeneous cloud where $N_i(\bar{r}) - N_e(\bar{r}) \neq 0$. Its structure varies, depending on the traveling direction of the body with respect to the vector of the magnetic field H_0. An electric field arises owing to the difference between the electron and ion trajectories. Of course, the effect of the body potential φ_0 may also be considerable. Collisions between particles exert an influence only at great distances from the body, since the mean free path of the particles exceeds the size of the body and the Larmor radii. Therefore, at distances of the order of the mean free path of the particle the perturbed region gets smoothed out.

We shall describe the nature of the disturbance in particle concentration in the near and far zones aft of the body.

The near zone is the region aft of the body at distances r of the order of the linear dimension of the body, i.e. at distances where

$$|\bar{r}| \sim \rho_0, \qquad |\bar{r}| < (V_0/v_i)\rho_0. \tag{4}$$

The far zone is the region of the distances

$$|\bar{r}| \gg (V_0/v_i)\rho_0. \tag{5}$$

Near zone. The distribution of the ion and electron concentrations in the near zone has been calculated while neglecting only the effect of the electric field on the ion motion. Here, the ion motion coincides with the neutral- /10 particle motion when the magnetic field $\bar{H}_0 = 0$. In cases where $\rho_{H_i} > 1$, the effect of the magnetic field on the ion motion in the vicinity of the body decreases markedly. This gives reason to believe that, at $V_0/v_i \gg 1$, the principal properties of the concentration distribution obtained for neutral particles at $|\bar{r}| \sim \rho_0$ also apply to a large extent to ions, i.e., $N_i(\bar{r}) \approx n(\bar{r})$ even when the effect of the electric field is taken into account. Here, it is borne in mind that the body is not artificially charged to extremely high potentials $\varphi_0 \gg$ $\gg \varkappa T/e$.

In the near zone, the shape of the body and its position with respect to its direction of motion are important factors, as is specifically evident from Figs.1, 2. Figure 1 shows the lines of equal values of the ratio of particle

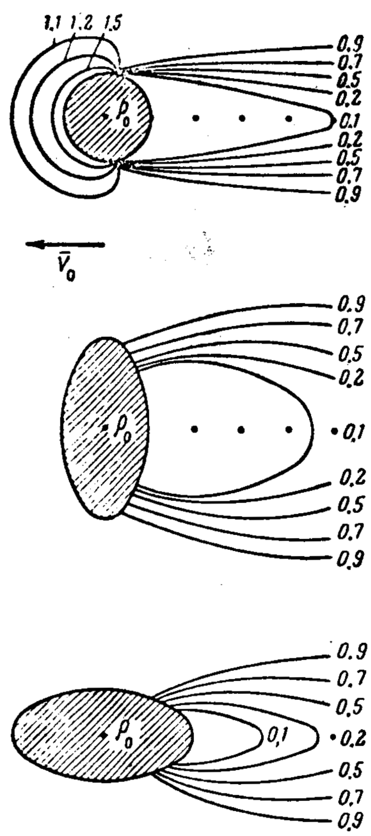

Fig.1

concentration to undisturbed concentration $[N_1(r, \theta)]/N_0$ for a sphere (Bibl.5) and an ellipsoid (Bibl.6), while Fig.2 shows $N_1(r, \theta)/N_0$ as a function of z_0/ρ, where z_0 is the distance from the surface of the body and ρ is the linear scale of the body along the axis of its motion ($\theta = 0$). In Fig.2 the radius ρ_0 is taken as the ρ for a sphere and a circular plate; for a square plate the linear scale $\rho = \sqrt{S_0/\pi}$, where S_0 is the area of the plate; for an ellipsoid, $\rho = \sqrt{\rho_1 \rho_2}$, where ρ_1 and ρ_2 are its semiaxes. Such a choice of ρ is based on the fact that the cross section of the body characterizes the body shadow effect (Bibl.2, 5). Figures 1, 2 indicate that in the near zone, in the region of the body shadow, where $\sin \theta < \rho/r$, the particle concentration decreases and tends toward zero; the angular variation in $N_1(\theta, r = \text{const})$ is then very rapid. This is evident from Fig.3, which shows the angular dependence of $N_1(\theta, r = \text{const})$ at different

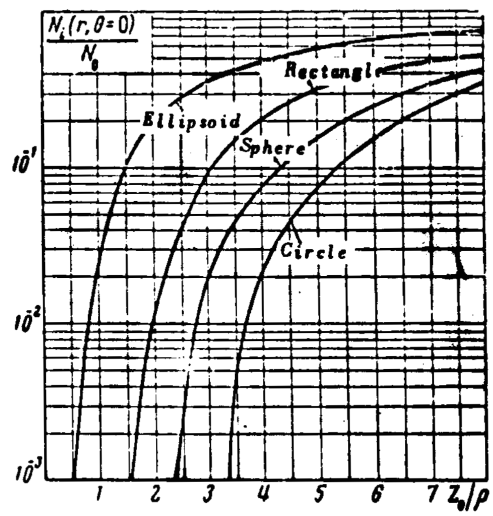

Fig.2

distances from the surface of the sphere (solid lines) and the ellipsoid (broken lines). The numerals denote distance expressed in radii of the sphere. For comparison, the circles show the results of measurements of the ratio between electron fluxes measured in two mutually perpendicular directions; the corresponding experimental curve is displaced with respect to its calculated counterparts and illustrates the rapid transition of $N_1(\theta)$ (Bibl.7) (see also below). /11

The effect of the magnetic field on the distribution $N_1(\bar{r})$, as was pointed out above, is not appreciable in the near zone. Calculations show that, without taking into account the electric field effect, this also holds true even when $\rho_0/\rho_{H_1} \sim 1$. It should be borne in mind, however, that in principle the combined effect of the electric field and the outer magnetic field $\overline{H}_0$ may prove to be appreciable also in the near zone. Therefore, until the appropriate calculations are accomplished, any definite conclusions on this matter would be premature. Note that certain properties of the distribution $N_i(\overline{r})$ have been obtained without taking into account the electric field at $\overline{H}_0 \neq 0$.

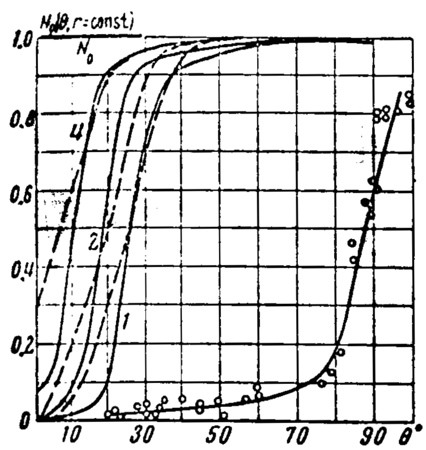

Fig.3

As the distance from the body increases the distribution $N_i(\overline{r})$, owing to the effect of $\overline{H}_0$, acquires a periodic structure. For example, when $\overline{V} \parallel \overline{H}_0$, for a sphere, the spatial period of $N_i(\overline{r})$ equals

$$\Lambda = 2\pi(V_0 / v_i)\rho_{Hi}.$$

Then, along the axis of motion of the body z, at $\theta = 0$,

$$\frac{N_i(z, 0)}{N_0} \sim \exp\left[-\frac{\rho_0^2}{4\rho_{Hi}^2 \sin^2\left(2\pi \frac{z}{\Lambda}\right)}\right], \qquad (6)$$

whence it follows that, for $z/\Lambda \ll 1$, the magnetic field effect vanishes and eq.(6) rigorously changes into a formula for neutral particles. Since the case $\overline{V}_0 \parallel \overline{H}_0$ is isolated, then, in the absence of collisions, the disturbance $\delta N = N_i(\overline{r}) - N_0$, as can be seen from eq.(6), does not decrease with distance from the body. This is because the ions move along spirals rigorously normal to the magnetic field and, if collisions are not taken into account, the rarefied zone will not be occupied by particles. In this case, it is of fundamental importance to take collisions into account when calculating $N(\overline{r})$ [cf.(Bibl.12)]; this will show that the periodic structure fades and disappears at distances of

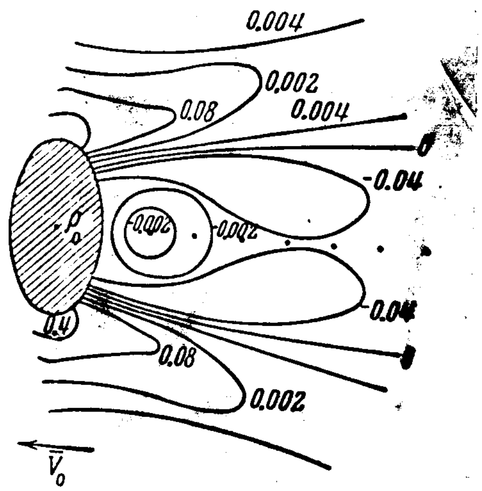

Fig.4

the order of the mean free path of the ions. At transverse motion of the body $\overline{V}_0 \perp \overline{H}_0$, the quantity $\delta N_i(\overline{r})$ decreases along the axis, generally in proportion to $1/z$; in this case, the variation in $N_i(\overline{r})$ is more complex than in the case of longitudinal motion but it is also of a quasiperiodic nature. Note that the disturbance in the concentration of neutral particles $n(\overline{r})$ decreases in direct proportion to z^{-2} rather than to z^{-1}, i.e., much more rapidly.

Calculation of the distribution of electron concentration $N_e(\overline{r})$ without /12
taking into account the effect of the magnetic and electric fields on ion motion shows that $N_e(\overline{r})$ differs markedly from $N_i(\overline{r})$ only at short distances from the body; in the far zone $N_e(\overline{r}) \sim N_i(\overline{r})$, correct to within $\lesssim 10^{-2}$.

In the near zone, the electron trajectories become more complex owing to the action of a sufficiently strong field formed by the potential φ_0 of the body and the attraction exerted by the ions, as can be seen in Fig.4 which gives the lines of equal values of $\delta N_e/N_0 = [N_i(\bar{r}) - N_e(\bar{r})]/N_0$ for an ellipsoid of revolution (Bibl.6). It should be kept in mind, however, that such a difference may apparently be appreciable only when the ρ_0/D ratio is not very high.

Various studies describing the results of local measurements of the concentration, composition, and other parameters of particles in the neighborhood of artificial satellites, performed with different types of probes, clearly indicate the complex nature of the behavior of the variables measured. This is particularly reflected in the wide spread of the individual measurements, due to the spin of the body - the variation in the position of the instrument with respect to the direction of the velocity vector V_0. Naturally, if the experimental results are analyzed without taking into account the angular dependence of the measured variables or their dependence on the distance from the body, the true picture of the state of the unperturbed medium may be considerably distorted. On the other hand, a consistent analysis of the angular function or distance function of, for example, particle concentration will make it possible to determine different variables in the neighborhood of the moving body with extreme accuracy. Wilmore et al (Bibl.7) give the angular dependence of the ratio between particle fluxes, measured simultaneously by means of two probes. One probe was mounted directly to the surface of the artificial satellite, while the other was extended at right angles to the first probe to a distance equal to 3 - 4 radii ρ_0 from the surface of the body. The results of the measurement (see circles in Fig.3) fairly satisfactorily confirm the theoretically expected rapid angular variation in concentration in the region of transition from small to large values of $N_e(\bar{r})$. These measurements, however, unfortunately are not amenable to a more precise treatment, since the two probes were located at different distances from the body and in a zone where the body shape exerts an extremely great influence*. It would be important to organize experiments of this kind with a spherically shaped body.

Far zone. For distances $|\bar{r}| \gg (V_0/v_i)\rho$ from the body, the problem of the distribution of electron concentration $N_e(\bar{r})$ has been solved for a sphere while taking into account both the electric field and the outer magnetic field H_0. The formulas for the disturbance $\delta N_e(\bar{r})$ have been, however, derived in $\bar{q}$-space, i.e., for Fourier components of the spatial distribution of electron concentration. Specifically, the quantity

$$N_{\bar{q}} = \int \delta N_e(\bar{r})\, e^{-i\bar{q}\bar{r}} d^3r, \tag{7}$$

has been calculated, since for $N_{\bar{q}}$ the solution of the kinetic equations (Bibl.2, 8) can be reduced to finite formulas. Therefore, to determine $\delta N_e(\bar{r})$, the integral (7) must be convoluted when utilizing the corresponding formulas for $N_{\bar{q}}$. Such calculations are fairly complex and have been successfully performed only for the case $H_0 = 0$. This makes it possible to determine the effect of the electric field on $\delta N_e(\bar{r})$ and to show that the latter differs in certain fundamental features from the corresponding distribution in the absence of that effect (Bibl.9). Before describing these features, it is expedient to point out certain properties of the quantity $N_{\bar{q}}$ that are significant to the problem of the interaction between the moving body and plasma.

If $H_0 = 0$, we have /13

$$N_{\bar{q}} = \pi\rho_0^2 \left(\frac{V_0}{v_i}\right)^2 \frac{N_0}{|\bar{q}|} \frac{Q(a)}{[2 + iaQ(a)]}, \tag{8}$$

* Here it is important to consider that the atmosphere contains light ions (He^+, H^+).

where

$$Q(a) = 2ie^{-a^2} \int_{-i\infty}^{a} e^{x^2}\,dx, \quad a = \frac{V_0}{v_i}\cos\chi, \tag{8a}$$

and χ is the angle between $\bar{q}$ and the velocity vector V_0.

In eq.(8) the electric field effect is determined by the denominator [2 + + iaQ(a)]. In fact, if this denominator is replaced by unity and the condition

$$a = (V_0/v_i)\cos\chi \gg 1, \tag{9}$$

is satisfied, it is possible that the disturbance in electron concentration in the far zone will be

$$\delta N_e(\bar{r}) = \int N_{\bar{q}} e^{i\bar{q}\bar{r}}\,d^3q = \frac{\rho_0^2}{r^2}\left(\frac{V_0}{v_i}\right)^2 N_0 \exp\left[-\left(\frac{V_0}{v_i}\right)^2 \mathrm{tg}^2\,\theta\right], \tag{10}$$

i.e., it accurately coincides with the disturbance in the neutral-particle concentration $\delta n(\bar{r})$. Thus, condition (9) for the far zone is a criterion of the

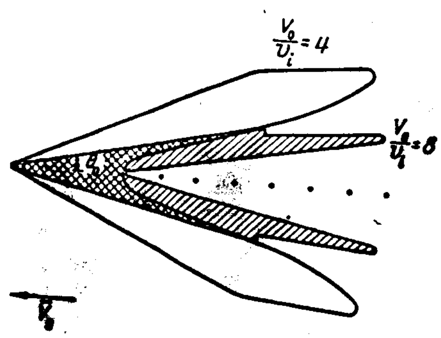

Fig.5

effect of the electric field and determines the region in which $\delta N_e(\bar{r})$ closely coincides with $\delta n(\bar{r})$. Convoluting the complete expression (8) for $N_{\bar{q}}$, we have instead of eq.(10)

$$\delta N_e = (\rho_0/r)^2 (V_0/v_i)^2 N_0 \times B(V_0/v_i, \theta), \tag{11}$$

where the exponent is replaced by the function $B(V_0/v_i, \theta)$, expressed through a complex integral. Figure 5 shows the numerical values of the function $B(V_0/v_i, \theta)$ calculated with respect to two values of V_0/v_i. It can be seen that the angular dependence of the disturbance in the electron concentration $\delta N_e(\bar{r})$ has the following major features that distinguish it from the disturbance in neutral-particle concentration.

First, maximum rarefaction is obtained in the vicinity of a cone with an angle of convolution

$$\theta_0 = \sin^{-1} v_i / V_0. \tag{12}$$

Second, along the axis of motion of the body, the rarefaction decreases markedly compared with what takes place in the case of neutral particles.

Thus, the electric field causes the electrons to be focused around the axis of motion of the body. Here, the focusing effect manifested itself in the far zone owing to the influence of a weak electric field on an equally small perturbation in the concentration $\delta N_e(\bar{r})$. It may be expected that in the near zone the relative influence of the electric field is less essential and does not alter markedly the angular dependence of $N(\bar{r})$, since in that zone the disturbance $\delta N_e(r)$ is intense, because $V_0/v_i \gg 1$. Note that the denominator in eq.(8) is the right-hand part of the variational equation describing the propagation of ion-plasma waves (see Section 6) if the following substitution is carried out

$$\frac{V_0}{v_i}\cos\chi \to \frac{V_{ph}}{v_i}\left(1 + i\frac{\gamma}{\omega}\right), \quad \frac{\omega}{k} \sim V_{ph}, \tag{13}$$

i.e., if it is assumed that the phase velocity of the plasma waves $\bar{V}_{ph} \sim \bar{V}_0 \cos\chi$. Since the electric field effect is considerable for $(V_0/v_i)\cos\chi \lesssim 1$, only ion-plasma waves with $V_{ph} \sim v_i \ll V_0$ can be a factor in the formation /14 of a perturbation aft of the body, if such waves are excited there. In this formulation, this problem requires a special study.

It has already been pointed out that the determination of $\delta N_e(\bar{r})$ requires not only taking into account the effect of the magnetic field but also calculating the more complex function of the type $B[V_0/v_i, [\bar{H}, \bar{V}_0]]$. At the same time, it is expedient to examine the special features of the variable $N_{\bar{q}}$, when $\bar{H}_0 \neq 0$, which in themselves, without calculating the integral (7), reveal important properties of the perturbation $\delta N_e(\bar{r})$.

Note first of all that, if the electric field effect is not taken into account, the magnetic field effect vanishes when the condition

$$q_{\parallel}^{-1} \ll \rho_{Hi}, \tag{14}$$

is satisfied, where $q_{\parallel}$ is the longitudinal component of $\bar{q}$. Thus, in $\bar{q}$-space, the condition (14), which characterizes a sufficient smallness of the longitudinal wavelength component compared with ρ_{H_i}, is equivalent in a coordinate space to the condition $r/\Lambda \ll 1$, or

$$r \ll \rho_{Hi}(V_0/v_i), \tag{15}$$

i.e., to a distance r sufficiently small compared with $\rho_{H_i}(V_0/v_i)$. Here, condition (15) is exactly the definition of the near zone at $H_0 \neq 0$, by contrast with definition (4) at $H_0 = 0$.

Further, it is important to consider that, in longitudinal motion of the body and neglecting the effect of the electric field on ion motion,

$$N_{\bar{q}} \sim \frac{1}{q_{\parallel}} \tag{16}$$

and tends toward infinity. As for the divergence of $N_{\bar{q}}$, this is perfectly comprehensible and equivalent to the fact (see above) that, for $\bar{H}_0 \parallel \bar{V}_0$, when the effect of the electric field and of collisions is not taken into account, the distribution $N_e(\bar{r}) \sim N_i(\bar{r})$ has a rigorously periodic structure aft of the body, a structure that does not change with increasing distance from the body. The electric field, on the other hand, upsets this periodicity even when collisions are not taken into account, which leads to a marked change in $N_{\bar{q}}$ and hence also in $N_e(\bar{r})$.

Of course, detailed calculations of the integral (7) for the case of $\bar{H}_0 \neq 0$ will make it possible to determine also the other features of the perturbation $\delta N_e(\bar{r})$ in the far zone. Even without rigorous calculations, however, it can be established that $\delta N_e(\bar{r}) \sim 1/r$ by analogy with what is obtained for $\delta N_i(\bar{r})$ when the effect of the electric field is not taken into account. As in the case of $\bar{H}_0 = 0$, when the effect of the electric field on ion motion is taken into account, the expression for $N_{\bar{q}}$ differs in that an appreciable denominator appears therein. In fact, at $\bar{H}_0 \neq 0$,

$$N_{\bar{q}}' = \pi N_0 \left(\frac{V_0}{v_i} \right) \rho_0^2 \rho_{Hi} \frac{C[(\bar{q}, \bar{V}_0), \rho_{Hi}]}{2 + i \dfrac{(\bar{q}\bar{V}_0)}{v_i} \rho_{Hi} C[(\bar{q}\bar{V}_0), \rho_{Hi}]}, \qquad (17)$$

where

$$C[(\bar{q}, \bar{V}_0), \rho_{Hi}] = \int_0^\infty \exp \left[i \frac{(\bar{q}\bar{V}_0)}{v_i} \rho_{Hi} x - \rho_{Hi}^2 \left(q_\parallel^2 x^2 + 4 q_\perp^2 \sin^2 \frac{x}{2} \right) \right] dx. \qquad (18)$$

The denominator in eq.(18), expressed in the form of an integral, leads, /15 in the formula, to a variational equation describing the ion-plasma waves for $\bar{H}_0 \neq 0$ and gives the spectrum of ion-plasma waves (see Section 6). The question of the role of these waves in the formation of the region of perturbation requires a special analysis.

One of the most interesting and important properties of the far zone is the scattering of electromagnetic waves in that zone, due to the disturbance in the electron concentration and hence also in the dielectric constant (Bibl.10). Since the wake of a rapidly moving body extends over a distance of the order of the mean free path of the particle, i.e., greatly exceeds the size of the body and, owing to the magnetic field effect, has a complex structure, its effective scattering cross section under certain conditions greatly exceeds the scattering on the body itself. We shall consider briefly the effect of the scattering of radio waves on the wake of the body (Bibl.2, 8, 11).

Scattering on the wake of the body. The differential effective scattering cross section due to the irregular formation $\delta N(\bar{r})$ the deviation of whose dielectric constant is small compared with its undisturbed value, is described by the Fourier component $N_{\bar{q}}$ [cf. eq.(7)] with the aid of the formula

$$d\sigma_e = \frac{1}{16\pi^2}\left(\frac{\omega_0}{c}\right)^4 \frac{|N_{\bar{q}}|^2}{N_0} \sin^2 \Psi_1 \, dO, \tag{19}$$

$$\left(\omega_0 = \frac{4\pi N_e^2}{m}\right)^{1/2},$$

where ω_0 is the plasma frequency of electrons; Ψ_1 is the angle between the electric vector of the incident wave and the wave vector of the scattered wave; $d\sigma_e$ defines the proportion of the energy of the scattered wave per unit solid angle dO. The corresponding calculations reduce eq.(19) to a formula containing integrals which are not expressed through known functions. Therefore, an analysis of $d\sigma_e$ requires numerical calculations.

For $H_0 \neq 0$, the effective cross section is a multilobed narrowly directional function with a principal maximum (Bibl.11) which is sharply expressed and reaches a particularly high value when the body is in longitudinal motion ($\bar{V}_0 \parallel \bar{H}_0$), i.e., when the angle between these variables is zero. In this case, the direction of the principal maximum is a mirror image of the direction of the wave vector from $\overline{H}_0$. The side maxima of $d\sigma_e$ are much smaller than its main maximum; thus, for altitudes of 300, 400, and 700 km the ratios between the side maxima and the main maximum at a frequency 10^7 (λ = 30 km) are:

300 km	$1.7 \cdot 10^{-1}$,	$1.6 \cdot 10^{-2}$	[illegible]	. . . . .
400 "	$0.9 \cdot 10^{-1}$,	$7.6 \cdot 10^{-3}$	[illegible]	. . . . .
700 "	$2.1 \cdot 10^{-2}$	$4 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	. . . . .

The side maxima are displaced with respect to the main maximum by the angles $\vartheta \approx 5, 9, 13^\circ \ldots$, while the width of the main maximum $\Delta\vartheta_m \sim (1 - 1.5)^\circ$. Thus, scattering due to the wake of the body is chiefly determined by the main maximum and will be considerable if the angle α between $\overline{V}_0$ and $\overline{H}_0$ is smaller than or of the order of the width of the main maximum. At $\alpha > \Delta\vartheta_m$, the quantity $d\sigma_e$ decreases in proportion to the ratio of the side maxima to the main maximum.

The effective cross section for this range of altitudes of the ionosphere increases with altitude owing to the effect of the decrease in the number of collisions, which offsets the effect of the decrease in the electron concentration and reduces $d\sigma_e$. As the wavelength increases, $d\sigma_e$ rapidly increases. Both functions are shown in Fig.6 for a sphere with the radius ρ_0 = 1 m; the same diagram also shows the ratio $d\sigma_e/d\sigma_0$ as a function of the effective scattering cross section of a metal sphere of the same size. It can be seen that the /16 effect of wake-induced scattering exceeds that of the scattering due to the body itself by a factor of several hundred. However, it manifests itself at the observation point in the form of a sharp, brief (one second or less) burst. Therefore, the scattering effect can be experimentally detected only under definite conditions and requires a precise organization of the experimental setup. Experiments of this kind are also of fundamental interest, in particular as a method of verifying the completeness of the theory of the interaction between the moving body and the plasma.

Assuming that $\overline{H}_0 = 0$, the calculation of $d\sigma_e$ is simplified. The width of the scattering region, under the above conditions reaches $10 - 12^\circ$, i.e., it is 10 and more times as wide as the main lobe of $d\sigma_e$ for $\overline{H}_0 \neq 0$. When $\rho_0 \sim 10^3$ cm, $d\sigma_e$ is less than the $d\sigma_0$ of the sphere itself, and only in the case of small bodies ($\rho_0 \lesssim 50$ cm) does $d\sigma_e$ exceed $d\sigma_0$ by 10 or more times.

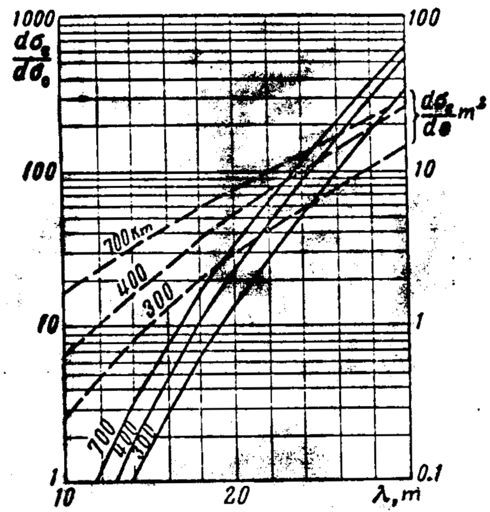

Fig.6

B. Quasiquiescent body, $V_0/v_i \ll 1$. The properties of the neighborhood of a body moving in plasma, as examined above, apply near the Earth, apparently up to altitudes of ~1500 - 2000 km. Upward of these altitudes, the case $V_0/v_i \sim 1$ gradually begins to prevail and the nature of the perturbation in particle concentration becomes different. Moreover, in those regions, ρ_0/D decreases rapidly, i.e., the size of the body becomes commensurate with the Debye radius and the potential of the body exerts an appreciable influence. Further, the ratio ρ_0/ρ_{He} gradually approaches unity, which alters the effect of the magnetic field on the electron motion. Thus, the medium III (see Table 2) is a transition region for which it is difficult to refine the theory.

At distances of (5 - 10) and more earth radii (media IV and V) there exist conditions more amenable to theoretical calculation. There,

$$\frac{V_0}{v_i} \ll 1, \quad \frac{\rho_0}{D} \lessapprox 1, \quad \frac{\rho_0}{\rho_{Hi}} \ll 1, \quad \frac{\rho_0}{\rho_{He}} \ll 1. \tag{20}$$

The body may be considered at rest and the influence of its potential φ_0 by then is decisive for a number of phenomena.

So far, however, theoretical calculations for $V_0/v \ll 1$ have been performed only with respect to cases of large ($\rho_0/D \gg 1$) and small ($\rho_0/D \ll 1$) bodies in the absence of a magnetic field ($\overline{H}_0 = 0$) (Bibl.2, 13, 14). The corresponding results apparently may serve to describe the effects anticipated in the plasma of the type of media IV and V.

The distribution of charged particle concentration $N(\overline{r})$ around a quasi-quiescent body is determined by the value φ_0 and by the nature of the potential distribution $\varphi(\overline{r})$ of the body; the reflecting properties of the body surface itself are a major factor here. The quantity φ_0 determines the difference between electron distribution $N_e(\overline{r})$ and ion distribution $N_i(\overline{r})$.

With respect to the nature of trajectories of charged particles, which depend on the total particle energy at a given point, i.e., on $\epsilon = Mv^2/2e + \varphi(\overline{r})$, two types of particle motion appear around the body: finite N_{fin} and infinite N_{inf}. Thus the concentration /17

$$N(\bar{r}) = N_{fin}(\bar{r}) + N_{inf}(\bar{r}). \tag{21}$$

<u>Finite particles</u>. A particle is termed finite if it is in a closed orbit around the body. Such an orbit may arise if $\epsilon = Mv^2/2 + e\varphi(\overline{r}) < 0$ in the case of a gravitational potential: positive for electrons and negative for ions. Since a body moving in the ionosphere and in the interplanetary medium is pre-

dominantly negatively charged, most of the finite particles are ions. The formation of finite orbits is mainly based on inter-particle collisions, since the particles incident on the body cannot be trapped into the orbits winding around the body, without releasing their energy. In the absence of collisions, the particles incident on the body are absorbed by its surface without being reflected from it.

The concentration of finite particles may greatly increase around the body, since they gradually accumulate there. Thus, in the case of an equilibrium distribution

$$N_{fin} = N_0 \exp\left[\frac{|e\varphi(\bar{r})|}{\varkappa T}\right] \qquad (22)$$

and if $|e\varphi| \gg \varkappa T$, the concentration $N_{fin} \gg N_0$.

In most of the cases of interest here, the calculation of N_{fin} is extremely complicated. The results obtained for electrons attracted to an absorbable Coulomb center, if they collide with neutral particles, may up to a point characterize the expected perturbation in the vicinity of the body due to finite particles. At distances $r > \sqrt{M/m}\rho_0$ from the body, i.e., near its surface, we have

$$N_{fin} \approx \frac{4}{3\sqrt{\pi}} N_0 \left[\frac{|e\varphi(r)|}{\varkappa T}\right]^{3/2} \left[\frac{2}{5}\frac{|e\varphi(r)|}{\varkappa T} + 1\right], \qquad (23)$$

at $\varphi(r) = Q_0/r$, where Q_0 is the charge of the body. Equation (23) indicates that, for $|e\varphi| \sim 2\varkappa T$, the concentration N_{fin} exceeds the undisturbed particle concentration by a factor of nearly 4.

<u>Infinite particles</u>. If the particle energy ε at a given point near the body is $Mv^2/2 + e\varphi(\bar{r}) > 0$, then the particle cannot revolve about the body and only infinite trajectories will form. The boundary line between the finite and

infinite particle regions depends largely on $\varphi(r)$ and is determined by the velocity boundary value which, in turn, depends on the specific conditions. In this connection, the field may be either attracting or repelling. Depending on the sign of the potential we will denote the infinite particles by either N_{inf}^{+} or N_{inf}^{-} and we will now examine the concentrations of these particles for two cases: small ($\rho_0/D \ll 1$) and large ($\rho_0/D \gg 1$) bodies.

For a small non-absorbing quiescent body ($V_0 = 0$), the concentration of attracting particles at distances of less than the Debye radius from the surface of the body, where the potential falls close to the Coulomb law $\varphi(r) = \varphi_0(\rho_0/r)$, will be

$$N_{inf}^{+} = N_0\left\{\frac{1}{\sqrt{\pi}}\sqrt{\frac{|e\varphi_0|}{\varkappa T}\frac{\rho_0}{r}}\left(1+\sqrt{1-\left(\frac{\rho_0}{r}\right)^2}\right)+\right.$$
$$+\frac{1}{2}\left[1-\Phi\left(\sqrt{\frac{|e\varphi_0|}{\varkappa T}\frac{\rho_0}{r}}\right)\right]\exp\left(\frac{|e\varphi_0|}{\varkappa T}\frac{\rho_0}{r}\right)+\frac{1}{2}\sqrt{1-\left(\frac{\rho_0}{r}\right)^2}\times$$
$$\left.\times\left[1-\Phi\left(\sqrt{\frac{|e\varphi_0|}{\varkappa T}\frac{r}{r+\rho_0}}\right)\right]\exp\left(\frac{|e\varphi_0|}{\varkappa T}\frac{r}{r+\rho_0}\right)\right\}$$
$$\left(\Phi(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-u^2}du\right), \qquad (24)$$

where $\Phi(x)$ is the probability integral. Here and below, the distance r is reckoned from the center of the body. For a Coulomb center, at $\rho_0 \to 0$ and $\varphi(r) = Q_0/r$, we have /18

$$N_{inf}^{+} = N_0\left\{\frac{2}{\sqrt{\pi}}\sqrt{\frac{|e\varphi(r)|}{\varkappa T}}+\exp\left(\frac{|e\varphi(r)|}{\varkappa T}\right)\left[1-\Phi\left(\sqrt{\frac{|e\varphi(r)|}{\varkappa T}}\right)\right]\right\}. \qquad (24a)$$

For repelled particles we have, in place of eqs.(24) and (24a), correspondingly

$$N_{inf}^{+} = \frac{N_0}{2}\left\{1+\Phi\left(\sqrt{\frac{|e\varphi_0|}{\varkappa T}\frac{r-\rho_0}{r}}\right)+\sqrt{\frac{r^2-\rho_0^2}{r^2}}\times\right.$$

$$\times\left[1-\Phi\left(\sqrt{\frac{|e\varphi_0|}{\varkappa T}\frac{r}{r+\rho_0}}\right)\right]\exp\left[\frac{|e\varphi_0|}{\varkappa T}\frac{\rho_0^2}{r^2+r\rho_0}\right]\Bigg\}\exp\left[-\frac{|e\varphi_0|}{\varkappa T}\frac{\rho_0}{r}\right]$$

$$N_{\inf}^{-}=N_0\exp\left[-\frac{|e\varphi(r)|}{\varkappa T}\right]. \qquad (25)$$

The curves of N^+/N_0 and N^-/N_0 as a function of $(r-\rho_0)/\rho_0$ for $\rho_0/D = 0.07 \ll 1$ are given in Fig.7 for two values of the body potential $|e\varphi_0|/\varkappa T = 2$ and 10. Near the body the concentration of attracted particles $N_{\inf}^+$ markedly increases, while the concentration of repelled particles (electrons) decreases. For the Coulomb center, the increase in $N_{\inf}^+$ is greater than for a small body of finite size. Thus, at $|e\varphi_0|/\varkappa T \gg 1$, eq.(24a) implies that

$$N_{\inf}^{+}=\frac{2}{\sqrt{\pi}}N_0\sqrt{\frac{|e\varphi_0|}{\varkappa T}}\times\left(1+\frac{\varkappa T}{2\,|e\varphi_0|}\cdots\right) \qquad (26)$$

and, at $|e\varphi_0|/\varkappa T \sim 10$, the ratio $N_{\inf}^+/N_0 \sim 4$.

In the presence of low velocities, when $V_0/v_i \ll 1$ but is non-zero (see Bibl.16), the particle concentration $N_{\inf}^+$ does not decrease in the rear of the Coulomb center as in the case of a rapidly moving body but rather increases. Thus, at $V_0/v_i \ll 1$ and $|e\varphi_0|/\varkappa T \gg 1$, we have

$$N_{\inf}{}^{+}=(N_{\inf}{}^{+})_{V_0=0}-\frac{2}{3}N_0\cos\theta\,\frac{V_0}{v_i}\sqrt{\frac{|e\varphi(r)|}{\varkappa T}}, \qquad (27)$$

where θ is the angle between the radius vector r and the velocity vector V_0. The explanation is that, at a sufficiently large potential, the particles are drawn toward the aft region of the body. In principle, this effect is also possible for large bodies but then in the presence of a very large potential φ_0.

Around the absorbing body, the concentration $N_{\inf}^+$ is determined by a more complex formula than eq.(24); we will not give it here. Near the body, $N_{\inf}^+$ decreases to half when $r \to \rho_0$.

A comparison of eqs.(23) and (24) shows that when $|e\varphi_0|/\varkappa T \gg 1$, the /19

concentration of finite particles exceeds that of the infinite particles:

$$\frac{N_{\text{fin}}}{N_{\text{inf}}^{+}} = \frac{4}{15}\left(\frac{|e\varphi(r)|}{\varkappa T}\right)^2. \tag{28}$$

For a large body, two zones in its vicinity are essential: the zone of a strong effect of Debye shielding which leads to the formation of a boundary layer in which the quasineutrality of plasma is disturbed, and the zone beyond the confines of the double layer. Normally, when the potential of the body is

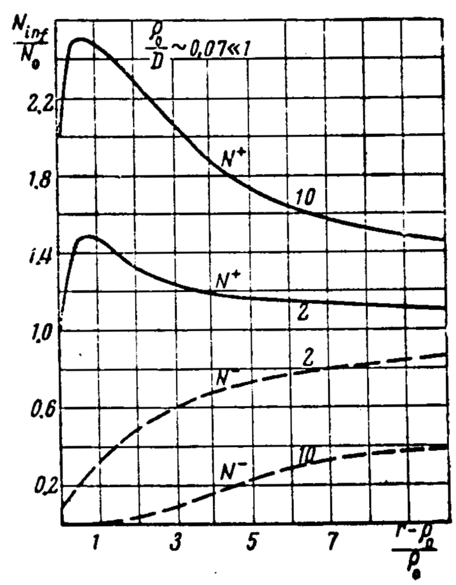

Fig.7

not too large, the double layer is of the order of D, i.e., much smaller than the radius of the body; it is important to bear in mind, however, that about the very surface of the body, sufficiently close to it, the nature of the variation in particle concentration may differ strongly from the concentration beyond the limits of the double layer. This is particularly important for bodies with high potentials when the double-layer zone is of the order of ρ_0. Accordingly, as in the case of a rapidly moving body, it is expedient to examine the near zone - a region of a thickness equal to that of the transition layer. For fairly low potentials, the near zone is determined by the distance $(r - \rho_0) \sim D$. For the potential

$$|\varphi_0| > \frac{\varkappa T}{e}\left(\frac{\rho_0}{D}\right)^{4/3}, \tag{29}$$

which in this case is the criterion of a high potential, the near zone is defined by the distance $(r - \rho_0) \sim \rho_0$. The far zone is correspondingly defined by the distances $r - \rho_0 > D$ or $r - \rho_0 \geq \rho_0$. The particle concentrations in both zones are determined by means of the same formulas but for different laws of variation in $\varphi(r)$ with distance.

The following formula for infinite particles, which provides a good approximation, has been derived for the concentration of attracted particles

$$N_{\inf} = \frac{N}{2}\left\{\exp\frac{|e\varphi(r)|}{\varkappa T}\left[1 - \Phi\left(\sqrt{\frac{|e\varphi(r)|}{\varkappa T}}\right) + \frac{2}{\sqrt{\pi}}\sqrt{\frac{|e\varphi(r)|}{\varkappa T}}\right] + \right.$$

$$\left. + \sqrt{\frac{r^2 - \rho_0^2}{r^2}}\exp\left[\frac{|e\varphi(r)|/\varkappa T(\rho_0^2/r^2) - |e\varphi_1(r)|/\varkappa T}{(\rho_0^2 - r^2)/r^2}\right]\right\} \tag{30}$$

where $\varphi_1(r)$ is the potential at the double-layer boundary.

For the concentration of repelled particles, we have

$$N_{\inf}^{-} = \frac{N_0}{2}\left\{1 + \Phi\left(\sqrt{\frac{|e\varphi_0| - |e\varphi(r)|}{\varkappa T}}\right) + \sqrt{\frac{r^2 - \rho_0^2}{r^2}} \times \right.$$

$$\times \left[1 - \Phi\left(\sqrt{\frac{\rho_0^2|e\varphi_0| - r^2|e\varphi(r)|}{(r^2 - \rho_0^2)\varkappa T}}\right)\right] \times$$

$$\left. \times \exp\left[\frac{\rho_0^2|e\varphi_0| - r^2|e\varphi(r)|}{(r^2 - \rho_0^2)\varkappa T}\right]\right\}\exp\frac{|e\varphi(r)|}{\varkappa T}. \tag{31}$$

In the near zone, eqs.(30) and (31) are considerably simplified. /20

A major problem is to calculate the $\varphi(r)$ function about the body in both zones. The results of numerical integration of $\varphi(r)$ in the near zone for $|e\varphi_0|/\varkappa T = 10$ and the values of the concentrations of infinite particles determined by means of $\varphi(r)$ for the potential $e\varphi/\varkappa T = 10$ are given in Fig.8. Fig.9 presents the corresponding findings for the far zone. Naturally, the curves of $\varphi(r)$ and N_{inf} osculate at the double-layer boundary. Figure 8 shows that, in

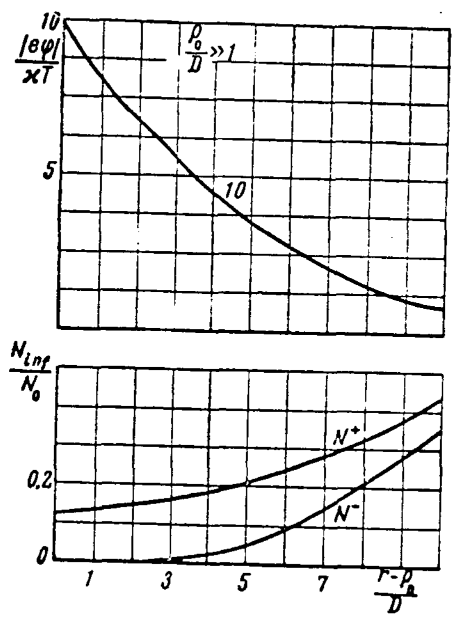

Fig.8

the near zone, the concentration not only of the repelled but also of the attracted particles decreases. This is due to the fact that the velocity of the attracted particles in the double layer increases, while their flux is preserved, which leads to a decrease in particle concentration. In the presence of a very high body potential, satisfying the criterion (29), the distribution of attracted particles in the near zone is more complex, but N_{inf}^+ is also smaller than the undisturbed particle concentration.

The nature of the concentration distribution varies considerably around a completely reflecting body. In the presence of absolute reflection, the con- /21

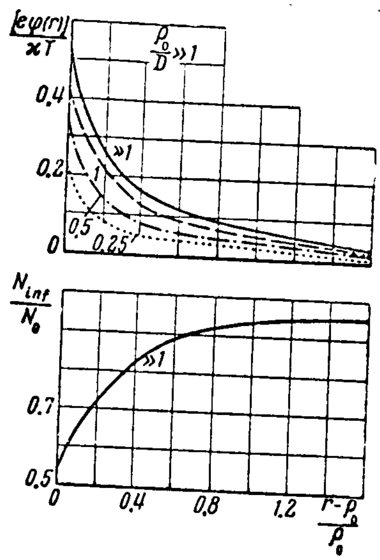

Fig.9

centration may increase sharply in the immediate vicinity of the body. In Fig.10 the results of calculations for $|e\varphi_0|/\varkappa T$ = 5 and 10 are given, when the

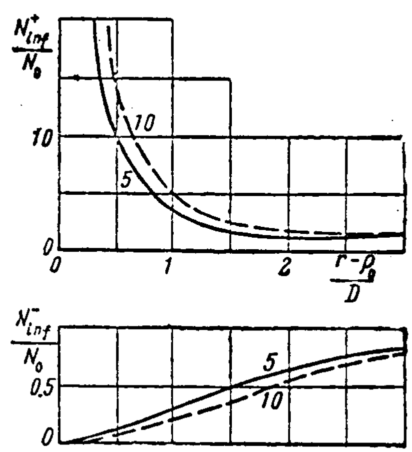

Fig.10

reflection factor is close to unity. Apparently this case is rarely encountered in reality. Intermediate cases, i.e., cases of partial reflection and absorption, however, actually occur, which greatly complicates the processes about the body.

It can be seen from the above discussion that the charged particle concentration is greatly disturbed in the vicinity of the spacecraft or artificial satellite, even at large distances from the Earth (media IV and V), where $V_0/v_i \ll 1$. The nature of the ion concentration distribution differs markedly

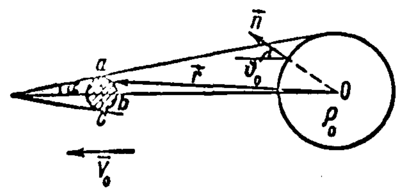

Fig.11

from that of the electron concentration distribution. The former particles are repelled from the body and move only in infinite trajectories, while the latter at the same instant are attracted and have both finite orbits and infinite trajectories. No doubt, the real picture is even more complex; for example, an anisotropy should arise in the particle distribution, owing to the effect of the Earth's magnetic field, and a number of other factors as well should be present, particularly those relating to the effect of the shape of the body.

In conclusion, it is worth noting the following: The particle distribution in the vicinity of the body sets in rapidly, so that the perturbation is entrained by the body and its nature changes slowly in accordance with the changes in external conditions. This means that if a device smaller than the body, such as a particle-capturing probe, is located near the body, it will collect the particles in the amounts in which they are present near the body and record the state of the perturbed region rather than that of the unperturbed medium. Depending on the design and position of the device with respect to the body, there may arise a natural perturbation in the neighborhood of the device itself, which will further complicate the overall picture.

Section 4. Particle Flux in the Vicinity of the Body

The question of the particle flux about an artificial satellite occupies an important place in the problem under consideration. This is due to the fact that various devices used for investigating unperturbed plasma are based on the particle-capture principle, i.e., on measurements of the total particle flux

$$J = \int j ds, \tag{32}$$

where the flux density per unit area at any point on the body surface is

$$j = \overline{N(\bar{r})\bar{v}} = \int v_n f(\bar{r}, \bar{v}) d^3v. \tag{33}$$

In eq.(32), the integration is performed over the entire surface of the body (or probe). In eq.(33), v_n is the normal velocity component at a given /22 point on the surface while $f(\overline{rv})$ is the distribution function. To calculate the flux, the flux density must be computed, i.e., it is necessary to solve the system of equations (1) and derive the distribution function on taking into account the potential distribution $\varphi(\bar{r})$ about the body and the constant magnetic field $\bar{H}_0$. So far however, the flux density with respect to $\bar{H} \neq 0$ has never been calculated. On taking into account the effect of $\varphi(\bar{r})$, on the other hand, certain results have been obtained with respect to a series of particular cases.

A. Rapidly moving body, $V_0/v_i \gg 1$. The simplest conditions exist ahead of a rapidly moving body with respect to ions, i.e., in media of the types I and II, since there the kinetic energy of a particle in the incident flux $Mv_0^2/2 \gg \gg e\varphi(r)$. In this case the ion flux nearly coincides with the neutral particle flux. Therefore, substituting the Maxwell distribution function (2) in eq.(33), we have

$$j_i \approx j_n = \frac{N_0}{2}\left\{\frac{v_i}{\sqrt{\pi}}\exp\left[-\left(\frac{V_0}{v_i}\right)^2\cos^2\vartheta_0\right] + V_0\cos\vartheta_0\left[1+\Phi\left(\frac{V_0}{v_i}\cos\vartheta_0\right)\right]\right\} \tag{34}$$

where ϑ_0 is the angle between the velocity and the normal to the surface (Fig.11). Equation (34), strictly speaking, is valid until

$$\frac{M(v_0\cos\vartheta_0)^2}{2} \gg e\varphi \gtrsim \varkappa T, \quad \frac{V_0\cos\vartheta_0}{v_i} \gg 1. \tag{35}$$

Therefore, in place of eq.(34), we have the simple formula

$$j_i \simeq N_0 V_0 \cos\vartheta_0. \tag{36}$$

Usually it is exactly eq.(36) that is used for analyzing experimental data. For total flux, eq.(34) is integrated over the probe surface; for a sphere we have

$$J = \pi\rho_0^2 N_0 V_0\left[1+\frac{1}{2}\left(\frac{v_i}{V_0}\right)^2\right], \tag{36a}$$

provided the condition $V_0/v_i \gg 1$ satisfied.

The flux of the ions reflected from the leading edge of the body may be determined in the same manner as for neutral particles, on merely taking into account the difference between the reflection factors of ions and neutral particles. In the case of mirror reflection from the front surface of the body, e.g. in the case shown in Fig.11, if the shadow effect of a small body ($\sin\alpha <$ $< v_i/V_0$) in the region (abc) is neglected, we have

$$j_{ir} \simeq V_0 N_i(\bar{r})\cos\vartheta_r, \tag{37}$$

where ϑ_r is the angle between the normal to the surface of the small body and the velocity V_0, while $N_i(\bar{r})$ is the ion concentration at the investigated point of the region (abc), obtained in the absence of a small body (Bibl.15, Fig.1). Taking the shadow effect into account, i.e. at $\sin\alpha \gtrsim v_i/V_0$, the concentration of reflected particles, of course, will also decrease at the point b, for example, while maintaining the condition $(V_0/v_i)\cos\vartheta \gg 1$ we obtain

$$j_{ir} \simeq V_0 N_i(r) \exp\left[-\left(\frac{V_0}{v_i}\right)^2 \sin^2\alpha\right], \qquad (38)$$

i.e., the flux density is exponentially small. An analogously exponential attenuation of the flux in the shadow zone will be present if the body surface does not reflect particles. Hence it is clear that a formula of the type of eq.(36a) for total flux must be used with great caution.

Aft of the moving body, i.e., in the zone of rarefaction, the effect of the distribution $\varphi(r)$ becomes essential to calculating the ion flux, and the neutral particle formulas are no longer applicable. For neutral particles, eq.(34) can be replaced, aft of the body, by /23

$$j_n = \frac{n_0}{2}\left\{\frac{v_i}{\sqrt{\pi}} \exp\left[-\left(\frac{V_0}{v_i}\right)^2 \cos^2\vartheta_0\right] - V_0\cos\vartheta_0\left[1-\Phi\left(\frac{V_0}{v_i}\cos\vartheta_0\right)\right]\right\} \qquad (39)$$

if, in the region (V_0/v_i), $\cos\vartheta_0 \gg 1$ (on the body axis)

$$j_n \simeq \frac{n_0}{4\sqrt{\pi}} v_i \left(\frac{v_i}{V_0}\right)^2 \exp\left[-\left(\frac{V_0}{v_i}\right)^2\right] \to 0, \qquad (40)$$

i.e., the flux is exponentially small.

The electron flux ahead and, partly, aft of the body must be calculated as for a quasiquiescent body, since $V_0/v_i \ll 1$.

B. Quasiquiescent body, $V_0/v_i \ll 1$. If the field is absent and the body is of the absorbing kind, then we will have, as for neutral particles,

$$j_{0i} = j_n = \frac{N_0}{2\sqrt{\pi}} v_i, \qquad j_{0e} = \frac{N_0}{2\sqrt{\pi}} v_e, \tag{41}$$

which is readily derived, in particular, from eq.(34).

If the field is present, the flux of both finite and infinite particles must be taken into consideration. The role played by the former, however, is minor about the absorbing body, since finite orbits intersecting the body are absent. In practice this case is often the most interesting. As for the body itself, it may be either attracting or repelling. Therefore, infinite particles of both kinds must be taken into account. The flux of repelled particles is readily calculated, since in this case the Maxwell-Boltzmann distribution applies. Repulsion results in cutoff of the region of the particle spectrum for which $Mv^2/2 \leq e\varphi(\bar{r})$ at a given point $\bar{r}$. To sum up, the flux of repelled infinite particles is smaller than the flux j_0 at $\varphi_0 = 0$, namely,

$$j_{inf}^- = j_0 \exp\left[-\frac{|e\varphi(\bar{r})|}{\varkappa T} \right]. \tag{42}$$

The greatest contribution to the flux is thus made by the attracted infinite particles. The calculation of j_{inf}^+ requires a rigorous solution of the system of equations (1). For a quiescent sphere, the density of the flux of infinite particles is

$$\begin{aligned} j_{inf}^+ = j_0 \Bigg\{ & \frac{|e\varphi_\infty|}{\varkappa T} \left(\frac{\rho_0}{r^2} \right)^2 + \frac{r_{min}^2}{r^2} - \left(\frac{r_{min}^2 - r^2}{r^2} \right) \exp \Bigg[\frac{|e\varphi(r_{min})|}{\varkappa T} + \\ & + \frac{r_{min}}{2} \left(\frac{d(e\varphi(r)/\varkappa T)}{dr} \right)_{r_{min}} \Bigg] + \frac{2}{r^2} \int_{r_{min}}^{\infty} r_{max} \Bigg[1 - \\ & - \exp \left(\frac{|e\varphi(r_{max})|}{\varkappa T} + \frac{r_{max}}{2} \left(\frac{d(e\varphi(r)/\varkappa T}{dr} \right)_{r_{max}} \right) \Bigg] dr_{max} \Bigg\}. \end{aligned} \tag{43}$$

Here, φ_∞ is the asymptotic value of the potential $\varphi(r)$ at large distances from the body; r_{min} and r_{max} are certain characteristic distances that depend on the potential distribution in the vicinity of the body and hence depend on the distance. They are determined by means of differential equations which are not given here.

Thus, it is obvious that the calculation of the flux of attracted infinite particles is extremely laborious. The results of such calculations for certain specific cases are presented below.

For a small body ($\rho_0/D \ll 1$), eq.(43) can be used to directly derive a simple formula for the flux on a spherical body, which applies rigorously only when the potential of the body is not too large. If

$$\varphi_0 \leqslant \frac{\varkappa T}{e}\frac{D}{\rho_0}, \tag{44}$$

then

$$j^{+}_{int} = j_0\left[1 + \frac{|e\varphi_0|}{\varkappa T}\right]. \tag{45}$$

Note that the total flux in the absence of the field will be /24

$$J_{0i} = \int j_0 ds = 2\sqrt{\pi}\rho_0^2 N_0 v_i, \quad J_{0e} = 2\sqrt{\pi}\rho_0^2 N_0 v_e. \tag{46}$$

Equation (45) coincides with the Langmuir and Mott-Smith formula which is often used to analyze the results of measurements. Equation (43) gives the limits of its applicability. In practice, eq.(43) is valid for $\rho_0/D \ll 1$ so long as the potential of the body

$$\varphi_0 \ll \frac{\varkappa T}{e}\left(\frac{D}{\rho_0}\right)^8. \tag{47}$$

If a criterion inverse to eq.(47) is satisfied, i.e., for very large body potentials, the flux of attracted infinite particles will increase greatly

$$j^{+}_{int} = 0.95 j_0\left[\frac{|e\varphi_0|}{\varkappa T}\left(\frac{D}{\rho_0}\right)^{4/3}\right]^{6/7}. \tag{48}$$

Thus, for $|e\varphi_0|/\varkappa T\ (\rho_0/D)^8 = 5$ the ratio $J_{int}^{+}/J_0 = 40$ (!), if $\rho_0/D = 1.3$.

Note that if the velocity of the body $V_0 \ll v_i$ but is not exactly zero, the total flux [cf. eqs.(45) and (46)] is correct within a small correction (Bibl.15)

$$dI_{int}^{+} \simeq \frac{1}{3}\frac{V_0^2}{v_i^2}\left(1 - \frac{|e\varphi_0|}{\varkappa T}\right) J_0. \tag{49}$$

For a large body ($\rho_0/D \gg 1$) with a moderate potential

$$|\varphi_0| \ll \frac{\varkappa T}{e}\left(\frac{\rho_0}{D}\right)^{4/3},$$

[see eqs.(29) and (43)], we have

$$j_{int}^{+} = j_0\left\{1 + \frac{|e\varphi_\infty|}{\varkappa T}\frac{2}{\rho_0^2}\int_{\rho_0}^{\infty} r\left[1 - \exp\left(\frac{|e\varphi(r)|}{\varkappa T} + \frac{r}{2}\frac{d|e\varphi(r)|}{\varkappa T dr}\right)\right] dr\right\}. \tag{50}$$

The results of a numerical integration of eq.(50) are presented in Fig.12 which gives the ratio between the flux density of the attracted infinite part-

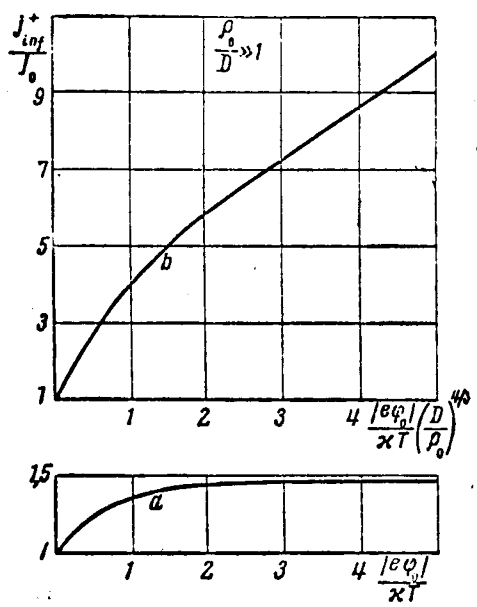

Fig.12

icles j_{int}^{+} and the unperturbed flux density j_0 near the surface of a large body ($\rho_0/D \gg 1$) as a function of low (a) and high (b) body potentials. It can be seen that, as φ_0 increases, the flux becomes constant within the limits of $j_{inf}^{+} \sim 1.5 j_0$. If, however, the potential φ_0 is sufficiently large, i.e.,

$$|\varphi_0| \geqslant \frac{\varkappa T}{e}\left(\frac{\rho_0}{D}\right)^{4/3}. \tag{51}$$

then it apparently often happens in reality (see Section 5) that

$$j_{inf}^{+} \approx 1{,}2 j_0\left[\frac{|e\varphi_0|}{\varkappa T}\left(\frac{D}{\rho_0}\right)^{4/3}\right]^{6/7}, \tag{52}$$

i.e., the flux increases greatly and may exceed by several times the unperturbed value of flux j_0 (Fig.12b).

The calculation of the particle flux at some distance from the body is more complicated. In this case, eq.(43) can no longer be used for the body surface ($r = \rho_0$), and the quantity $j_{inf}^{+}(\bar{r})$ must be calculated with respect to a given surface of another body (e.g. a probe, Fig.11) while taking into account the perturbation it introduces. Here it is also important to make allowance for the flux of reflected particles and for the shadow effect. As a result, the flux density at the probe is no longer a centro-symmetric function, and a calculation of the total flux requires integration of the complex function $j(\bar{r})$.

Section 5. Potential of the Body in a Plasma

The question of the potential of an artificial satellite is a highly /25 topical problem. This is not only because the perturbation in the vicinity of a body, in a number of cases, cannot be correctly determined unless the body potential is known; it is also perplexing that the theoretically expected potential which should be assumed by a body moving in a plasma is, at first glance, only a fraction of the potential often obtained in different experiments.

Let us evaluate the potential of a body in plasma. At some point on the body surface the potential is determined from the condition of equality of the electrons and ions adsorbed at this surface in unit time. Here, since the electron velocity $v_e \gg v_i$, the body should be negatively charged. In fact, let us first examine a body at rest, on which electrons and singly-charged ions are incident. Let us assume $N_e \approx N_i$ and $T_e \approx T_i$. At any point in the plasma, the ratio of their fluxes across a unit area is $j_e/j_i = v_e/v_i \gg 1$. Therefore, when such particles bombard a body, its surface will be charged until the fluxes at a given point become equalized. This is possible if the flux of electrons striking the body decreases, i.e., if the body acquires a repellent negative charge. Then the electron-flux density at the point s on the surface of the body will be

$$j_{es} = j_0 \exp[-|e\varphi(s)|/\varkappa T]. \tag{53}$$

The ion flux (see above) has a more complex dependence on the potential and increases with increasing $|\varphi_s|$ if $\varphi_s < 0$. Since, however, we are interested in the maximum expected values of φ_s, it may be assumed that, about the body, $j_{is} \simeq j_{i0} = (N_0/2\sqrt{\pi})\, v_i$ [see eq.(41)], i.e., j_{is} equals the flux at $\varphi_0 = 0$. This should lead to a small error. In fact, since the obtained values of φ_s are low, they are not much affected by the use of the potential-dependences of j_i given in the preceding Section. The equality between the absorbed electrons and ions at the body surface, taking into account their reflection factors ρ_e and ρ_i, yields the relation

$$j_{is}(1-\rho_i) = (1-\rho_e)\, j_{es} \tag{54}$$

or

$$v_i(1-\rho_i) = v_e(1-\rho_e)\exp\left[-\frac{|e\varphi_s|}{\varkappa T}\right], \tag{55}$$

whence it follows that

$$|\varphi_s| = \frac{\varkappa T}{e} \ln\left\{ \frac{v_e(1-\rho_e)}{v_i(1-\rho_i)} \right\}. \tag{56}$$

Proceeding from the premise that ρ_e and ρ_i are small, i.e., that the body mainly absorbs particles, we can find from Table 1 that, correspondingly, in the ionosphere (media I and II) and in the interplanetary medium IV

$$\varphi_s \approx (0.7 \div 1.3)\ \text{v}, \qquad \varphi_s \approx 2\,\text{v}.$$

for a body at rest.

In the ionosphere (media I and II), however, the potential acquired by a rapidly moving body must be estimated. For the leading edge of the body this potential is readily determined by using eq.(54) and substituting its expression for ion flux by eqs.(34) or (36). Ultimately, at cos ~ 1 (cf. Fig.11), we have

$$\varphi_s \approx \frac{\varkappa T}{e} \ln\left\{ \frac{v_e}{V_0} \frac{1-\rho_e}{1-\rho_i} \right\}, \tag{57}$$

and for a rapidly moving absorbing body ($\rho_e \approx 0$, $\rho_i \approx 0$) /26

$$\varphi_s \approx (0.4 - 0.9)\ \text{v}. \tag{58}$$

The potential φ_s aft of the body is difficult to calculate in practice since there are no sufficiently simple and exact formulas of the ion and electron flux densities for this region, if the electric field of the space charge is taken into account. For a metallic body whose potential should be constant, $\varphi_0 \approx \varphi_s$ everywhere on the surface in view of the fact that, though this specifically applies to the leading edge, the flux incident on the trailing edge is extremely small.

For a dielectric body with a nonuniform surface, the potential may vary greatly from point to point, particularly if the difference between the reflection factors ρ_i and ρ_e is taken into account. This picture is complicated by the different processes of emission of particles from the body surface and the photoeffect, which reduce the negative value of the body potential. Apparently, the potential at the trailing edge of a moving body will increase because of the decrease in the ion flux relative to the electron flux.

This accounts for the scatter of the experimental data presented in the literature. Thus, the findings by Sharp (Bibl.17) on the volt-ampere characteristics of a probe indicate that the potential of an artificial satellite (or, more exactly, of the portion to which the probe is attached) varied with the motion of the satellite virtually from zero to -(12 - 14) v, i.e., became much higher than the value of φ_s [see eq.(59)] obtained above. Such a situation presents a number of difficulties.

First, although in nature the establishment of the body potential is a complex process, the theoretical estimates of φ_s must be correct unless some major effects are overlooked.

Second, since the potential of the body is determined in the same experiments and with the same instruments as are used to measure particle fluxes, the doubt arises whether the erratic behavior of the potential may not be due to the unreliability of the method of principal measurements. In particular, this might be attributable to the frequent failure to employ correct theoretical formulas for analyzing the experimental findings.

Third, the fact of the absence of reliable data on the potential of the body at the moment of measurements makes the resultant data unsuitable for a sufficiently accurate interpretation.

Therefore, the development of alternate methods of determining the potential of the body is a highly important task. We believe that, in particular, simultaneous measurement of the potential at different distances from the body and a rigorous theoretical analysis of the data (Bibl.10) should be a sufficiently strict and pure method. Note that calculations of the field potential $\varphi(\bar{r})$ in the near zone of a rapidly moving body, particularly if the effect of the electric field on the ion motion for $\bar{H}_0 = 0$ is neglected, will lead to the following simple formulas. Ahead of the body, beyond the limits of the double layer ($\rho_0 \gg D$), we have

$$\varphi(\bar{r}) = \frac{\varkappa T}{e} \ln \frac{N_i(\bar{r})}{N_0}. \tag{59}$$

This corresponds roughly to $N_e \simeq N_i$. For the ionosphere (media I and II) in this region we have a maximum of $\varphi(\bar{r}) \lesssim \varkappa T/e = (0.1 - 0.3)$ v. In the double layer, i.e., near the very surface, the potential $\varphi(\bar{r})$ tends toward φ_0.

Downstream of the body, in the far zone, i.e. at distances $r > \rho_0 (V_0/v_i)$,

$$\varphi(\bar{r}) \approx \frac{\varkappa T}{e} \frac{\delta N_i(r)}{N_0}, \tag{60}$$

where $\delta N_i(r)$ can be determined by means of the formulas given in Section 3A. /27
At the double-layer boundary, $(r - \rho_0) \sim D$,

$$\varphi(\bar{r}) \approx \frac{\varkappa T}{e} \ln \left(\frac{\rho_0}{D} \right)^2 \tag{61}$$

and in the ionosphere (see Tables 1, 2) the potential reaches approximately $11(\varkappa T/e)$, i.e., will be of the order of (1.3 - 2.8) v. Clearly, downstream of the body, close to it, $\varphi(r)$ already markedly exceeds the potential φ_s upstream of the body [eq.(57)]. This demonstrates the validity of the above reasoning on the potential φ_s at the trailing edge of the body.

Section 6. Excitation of Longitudinal Plasma Waves

The problem of the excitation of oscillations and waves by a body moving in a plasma and of the nature of the stability of the perturbation arising in the vicinity of the body requires the solution of the nonlinear kinetic problem for a body of finite size. Here it is important to take into account the boundary conditions, which should appreciably affect the character of the stability. So far, however, we know of no successful investigations of this kind. Therefore, to assess the expected effects, an examination of the general properties of the variational relation will have to suffice. It ultimately turns out that, for the case of a single-temperature plasma, the expected excitation of the Cherenkov radiation type is apparently weak, since the Landau damping γ for these waves is of the order of the oscillation frequency ω. As is known, the damping of the waves becomes small only at $T_e \gg T_i$. In this case, however, the waves in plasma are of a hydrodynamic rather than of a kinetic nature and Langmuir-Tonks ion waves are excited. The damping γ becomes small and even positive when a sufficiently large directional relative velocity between electrons and ions exists in the plasma. This is the case of the so-called beam instability of plasma. With respect to a large body at rest, this case has been investigated by Jaffe (Bibl.21). It is not impossible that precisely such conditions may occasionally arise in the vicinity of an artificial satellite.

The variational equation for longitudinal plasma waves, taking into account electron and ion motion, at $\overline{H}_1 \neq 0$, has the form (Bibl.18, 19)

$$\frac{\omega^2}{v_{ph}^2} = \frac{\omega_0^2}{v_e^2}\left[\exp\left(-\frac{\omega^2}{\omega_H^2}\frac{v_e^2}{v_{ph}^2}\sin^2\vartheta\right)\sum_{-\infty}^{\infty} J(\beta_{e,n}) I_n\left(\frac{\omega^2}{\omega_H^2}\frac{v_e^2}{v_{ph}^2}\sin^2\vartheta\right) - 1\right] +$$
$$+\frac{\Omega_0^2}{v_i^2}\left[\exp\left(-\frac{\omega^2}{\Omega_H^2}\frac{v_i^2}{v_{ph}^2}\sin^2\vartheta\right)\sum_{-\infty}^{\infty} J(\beta_{i,n}) I_n\left(\frac{\omega^2}{\Omega_H^2}\frac{v_i^2}{v_{ph}^2}\sin^2\vartheta\right) - 1\right]. \qquad (62)$$

Here the wave number k is expressed by ω/v_{ph} taken as real, while v_{ph} is the phase velocity of the longitudinal waves, ϑ is the angle included by the wave vector k and the magnetic field $\overline{H}_0$; $I_n(\beta)$ is the Bessel function of the imaginary argument, namely, the function

$$J(\beta) = \beta \exp\left(-\frac{\beta^2}{2}\right) \int_{-i\infty}^{\beta} e^{\tau^2/2} d\tau$$

[cf. eq.(8a)],

$$\beta_{e,\,in} = \frac{1}{\cos\vartheta}\left\{\left(\frac{v_{ph}}{v_{e,\,i}} - n\frac{\omega_H\,(\text{ or }\ \Omega_H)}{\omega}\right) + i\frac{\gamma}{\omega}\frac{v_{ph}}{v_{e,i}}\right\}, \tag{63}$$

where γ is the Landau damping factor. At $\overline{H}_0 = 0$, the variational equation (62) has the simplified form

$$\frac{\omega^2}{v_{ph}^2} = \frac{\omega_0^2}{v_e^2}\left[J\left(\frac{v_{ph}}{v_e} + i\frac{\gamma}{\omega}\frac{v_{ph}}{v_e}\right) - 1\right] + \frac{\Omega_0^2}{v_i^2}\left[J\left(\frac{v_{ph}}{v_i} + i\frac{\gamma}{\omega}\frac{v_{ph}}{v_i}\right) - 1\right]. \tag{64}$$

Equations (62) and (64) contain two bracketed terms. These terms describe high-frequency (electron) and low-frequency (ion) plasma waves, respectively. One of these terms contains v_{ph}/v_e as the argument, and the other, v_{ph}/v_i. For high-frequency waves, /28

$$\frac{v_e^2}{v_{ph}^2}\frac{\omega^2}{\omega_0^2} = k^2D^2 = \left[J\left(\frac{v_{ph}}{v_e} + i\frac{\gamma}{\omega}\frac{v_{ph}}{v_e}\right) - 1\right]. \tag{65}$$

For low-frequency waves ($\omega \sim \Omega_0$) in the case in which $T_e = T_i$ and $v_e/v_i \gg 1$, eq.(64) reduces to the form of

$$\frac{v_i^2}{v_{ph}^2}\frac{\omega^2}{\omega_0^2} = \left[J\left(\frac{v_{ph}}{v_i} + i\frac{\gamma}{\omega}\frac{v_{ph}}{v_i}\right) - 2\right]. \tag{66}$$

The solution of the variational equation (65) for $\omega \sim \omega_0$ is represented by (Bibl.20):

$$\omega^2 = \omega^2 + 3(\varkappa T/m)k^2.$$

In the vicinity of $\omega \sim \omega_0$ we always have $v_{ph}/v_e \gg 1$, since the phase velocity here increases without bounds. For ω differing from ω_0, we have

$$v_{ph} \sim (\omega_0/\omega)v_c. \tag{67}$$

Since wanted is the Cherenkov-radiation type excitation caused by a body moving at a velocity V_0, the condition $v_{ph}/V_0 < 1$ or

$$V_0 > (\omega_0/\omega)v_e. \tag{68}$$

is a prerequisite here.

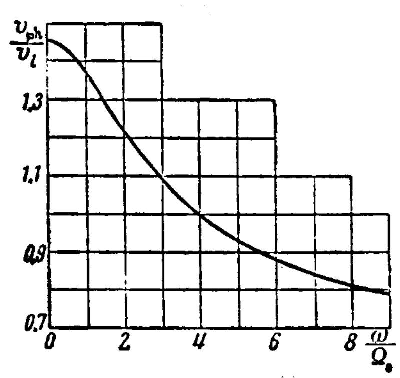

Fig.13

This last condition is satisfied only if $\omega_0/\omega \ll 1$, since $v_e/V_0 \gg 1$. However, eq.(68) is equivalent to the case $Dk \gg 1$. For this case, as shown relatively early by Landau (Bibl.20) when he first discovered the attenuation specific for plasma waves, γ is extremely large, namely,

(69)

since ξ, determinable from the equation $\xi e^{\xi^2/2} = 1\sqrt{2\pi}\,(kD)^2$, is of an order of magnitude equal to $\sqrt{\ln\,(kD)} \gtrsim 1$. Thus, high-frequency oscillations proportional to $\exp\,[i(\omega + i\gamma)t]$ are damped very rapidly. When the magnetic field is non-zero, the damping of high-frequency waves is also large; γ is determined by a relation of the type of eq.(69).

For ion-plasma waves in the case $T_e \sim T_i$ of interest here, the results of an analysis of eq.(66) for the region $v_{ph}/V_0 < 1$ are given in Figs.13 and 14*.

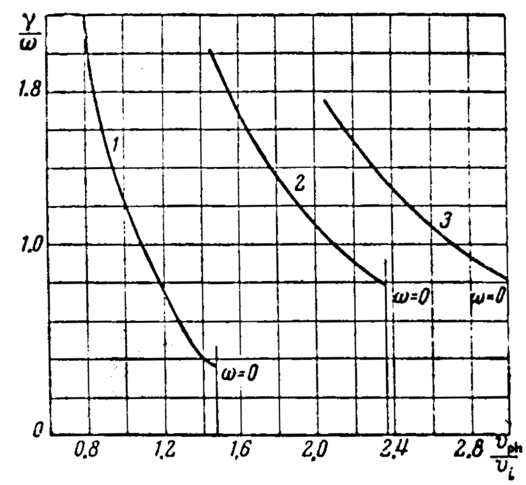

Fig.14

Figure 14 presents the ratio v_{ph}/v_i as a function of the ratio of the frequency ω to the ion plasma frequency Ω_0. It is obvious that, as the frequency decreases, the phase velocity increases, reaching a maximum $v_{ph} \approx 1.46\ v_i$ at $\omega = 0$. Thus, longitudinal waves with a phase velocity of $v_{ph} > 1.46\ v_i$ are impossible in a plasma, which is logical when considering that sonic waves are the limiting case of ion-plasma waves ($\omega = 0$). Figure 14 implies, in particular, that the velocity of sonic waves in a kinetic approximation exceeds the hydrodynamic velocity of sound.

The solution of eq.(66) has an infinite number of branches, i.e., a dis- /29
crete set of values of the frequency ω corresponds to each pair of values of

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* The author is indebted to N.I.Bud'ko, who calculated the curves given in Figs.13 and 14.

v_{ph} and γ satisfying eq.(66). Figure 14 shows only one branch $v_{ph}(\omega)$, while Fig.15, which gives γ/ω as a function of v_{ph}/v_i shows three branches of the solution for the variational equation (65). At the points $v_{ph}/v_i = 1.46$, 2.36, and 3.00, where $\omega = 0$, we have correspondingly $\gamma/\omega = 0.38$, 0.78, and 0.83. The branches (2, 3) describe waves with a phase velocity exceeding that of the branch (1), but the damping of these waves is much greater. From Fig.14 it can be seen that longitudinal ion-plasma waves are rapidly attenuated throughout the frequency range.

Section 7. Evaporation (Erosion) from the Surface of an Artificial Earth Satellite in Plasma

The plasma region surrounding an artificial satellite in the ionosphere or in the interplanetary medium apparently must be constantly occupied by "foreign" particles owing to evaporation, erosion, and other processes of liberation of particles from the surface of the body. This "contamination" of the plasma may be detected, for example, by mass-spectrometry. Molecules alien to the plasma should continually fly off the body surface and be ionized owing to solar radiation.

However, the process of this ionization is extremely slow. The ionization time is very long and approximately equals

$$t_i \sim \frac{1}{\sigma^{s/\varepsilon_i}} \sim 10^7\, sec, \tag{70}$$

where σ = cross section for ionization and s/ε_i is the flux of ionizing quanta per second. The time taken by the particles to recede to a certain distance from the body surface, for example, to the distance $r \sim 10^2$ cm, equals $r/v_s \sim$ $\sim 10^{-2}$sec. Therefore, in this region $N_s/n_s \sim 10^{-9}$, where n_s and N_s are the concentrations of extra neutral particles and electrons, respectively.

The rate of liberation of particles from the body surface is $v_s \sim \sim \sqrt{2\kappa T_s/M_s}$, where T_s denotes the surface temperature of the body and M_s is the mass of evaporated particles. Therefore, the particles at first recede slowly from the body. Gradually, at greater distances from the surface, they acquire the thermal velocity of the ambient medium and diffuse rapidly. Near the body itself, however, a sufficiently large concentration n_s of newly produced particles may exist, resulting in continuity of the action of the source. Thus, assuming that $v_s \sim 10^4$, which corresponds to the expected values of T_s and M_s at a distance from the body equal to its size, $\rho_0 \sim 10^2$ cm, which is traveled by the particle within 10^{-2} sec, in the presence of a particle flux of $j = \overline{(nv)}_s \sim 10^6 - 10^8$ atoms cm^{-2} sec^{-1} (see below), the average concentration apparently will be

$$n_s \sim (10^4 - 10^6)\ at.\ cm^{-3}. \tag{71}$$

The picture changes somewhat if aggregates of particles rather than individual particles are liberated at the surface.

Of course, the role played by the extra particles will be appreciable only if $n_0 \ll n_s$, i.e., at distances of > 5000 - 3000 km from the Earth.

In theory, it is hardly possible at present to calculate the flux $J_s = \overline{(nv)}_s$ of the particles produced under the action of various processes. Estimates are based solely on the results of experimental data obtained by means of artificial satellites and rockets. McKeown (Bibl.22), for example, gives the flux $J = \overline{(nv)}$ of particles liberated by a gold plate as a function of the altitude of the artificial satellite. The plate was positioned normal to the incident flux (the satellite was stabilized) and represented the electrode of a quartz-crystal oscillator. The loss of gold was determined according to the corresponding beat frequency of another oscillator. As the altitude increased from 216 km to 810 km the particle flux varied within the range

$$J = \overline{(nv)} \simeq (10^7 - 10^{10}) \ at.cm^{-2} sec^{-1}, \tag{72}$$

i.e., the evaporation rate was $\lesssim 5 \times 10^{-6}$ atoms per molecule of incident flux. /30

McKeown (Bibl.22) also gives the following values of J for metals (aluminum, zinc, iron, magnesium, lithium) with a surface temperature varying within the limits of $T_s \sim 100 - 1000^0$.

$$J = \overline{(nv)} \simeq (10^{10} - 10^{14}) \ at.cm^{-2} sec^{-1}. \tag{73}$$

Significantly, the sublimation rate of particles depends sharply on T_s and increases by 10^3 to 10^4 times when the temperature changes by a factor of 1.5 - 2. Of course, the region of T_s within which such a rapid increase in evaporation rate occurs, depends on the properties of the metal. This should be borne in mind when analyzing various data provided by an artificial satellite or a spacecraft whose surface consists of materials of different types and whose surface temperature varies within extremely wide limits. Note that the vacuum sublimation rates of such materials as polymers, nylon, sulfides, vinyl chloride, reach $\sim 3 \times 10^{-9}$ by weight of the material per second.

In the radiation belts, the erosion rate of matter due to collisions with protons of ~ 1 Kev energy is close to the lower limit obtained elsewhere (Bibl.23): $J \sim 10^7$ atoms cm^{-2} sec^{-1}. During the periods of solar flares, when protons with energies of 0.5 - 20 Kev are produced, $J \sim 10^8 - 10^{11}$ atoms cm^{-2} sec^{-1}, while the value at quiescent solar radiation (protons with ~ 3 Kev) is $J \sim 10^8$ atoms cm^{-2} sec^{-1}.

Various findings indicate that the erosion due to meteoritic matter lies within the limits of the range of values of J given above.

Conclusions. It was shown above that various phenomena occur in the vicinity of an artificial satellite or spacecraft moving in the ionosphere or interplanetary medium. The nature of this complex of phenomena depends both on the geometrical and physical properties of the body as well as on the properties of the plasma and the radiation fluxes in which the body moves. The investigation of these phenomena is of great scientific interest as an autonomous branch of plasma studies. Moreover, knowledge of the nature of these effects is also extremely important to the solution of a number of scientific-technical and practical problems. The exhaustive utilization of artificial satellites as laboratories for research on the ambient medium is impossible unless the influence of the above effects on the various experiments is taken into account, as we have repeatedly pointed out in earlier studies (Bibl.2, 3, 10).

Lack of space prevented the discussion of certain additional effects observed about the body. For example, the effect of the high-frequency field on plasma (Bibl.23) has not been investigated. A radiating antenna will create large fields in the plasma. This results in a strong pressure on the charged particles near the antenna and in a marked perturbation of the plasma. At the plasma frequency when $\omega \to \omega_0$, this effect becomes greatly magnified. Another effect, described elsewhere (Bibl.24), consists in that, on passing a radio-frequency field through two capacitor plates, with the body of the artificial satellites used as one of the plates, a weak direct current arises. When $\omega \to \omega_0$, the current intensity increases greatly, i.e., a distinctive detector resonance effect of the plasma is observed. So far no theoretical explanation has been advanced for this extremely interesting effect which is important to investigations of the plasma near the Earth. Moreover, the experiments described leave certain questions unanswered, such as the friction of electromagnetic origin, produced, for example, by the interaction between the electric and magnetic fields formed in the vicinity of the body and the outer magnetic field.

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